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FAST LUMINOSITY MONITOR FOR FCC-ee BASED ON THE LEP EXPERIENCE

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Abstract

The measurement of luminosity and beam divergence performed by the LEP-5 experiment at CERN based on the detection of photons from the single breamsstrahlung process $e^+e^- \to e^+e^-\gamma$ at the LEP interaction point 1 is briefly reviewed. A possible implementation of the same methodology for a very fast luminosity monitor at FCC-ee is preliminarly discussed.

INTRODUCTION

The measurement of luminosity at colliders is essential in view of two different objectives: (i) for cross section measurements, where an accurate knowledge of the integrated luminosity is required, and (ii) for machine performance optimization and operation, where a quick feedback from a fast luminosity monitor is desirable.

The luminosity at electron-positron colliders is commonly measured and monitored by detecting the QED Bhabha scattering (BS) process $e^+e^- \to e^+e^-$. An intense R&D program is on-going for the FCC-ee collider project to reach the ambitious goal of a precision of 10^{-4} on the absolute luminosity measurement around the Z pole by detecting BS events at very small angles [1]. It is worth reminding that at the Large Electron Positron collider (LEP), the second-generation of Bhabha luminosity monitor achieved on the absolute luminosity an experimental precision of 3.4×10^{-4} [2].

Before LEP, the idea to measure the luminosity using the QED process $e^+e^- \to e^+e^-\gamma$, i.e. the single bremsstrahlung (SB), also called radiative Bhabha scattering, was first exploited at ADONE in Frascati in the '70 [3], and then at VEPP in Novosibirsk [4]. The main feature of this process is that its cross-section slightly increases with energy, $\sigma_{SB} \sim \ln s$, unlike for the BS, whose cross-section decreases as $1/s$. Moreover the BS cross-section depends on the $e^\pm$ scattering angle θ as θ^{-4}, while almost all SB photons are extremely collimated with an angular distribution in a narrow cone in the forward direction $\theta_\gamma \simeq m_e/E$. This makes SB especially convenient at high energy machines as a faster *monitor process* than BS for the easily reachable high rates, as for instance at LEP and in all four beam energy configurations foreseen at FCC-ee, namely Z, WW, HZ and $t\bar{t}$, as shown in Table 1 (for the complete set of parameters used for the present study see Refs. [5, 6]).

In the following, the measurement of luminosity and beam divergence performed by the LEP-5 experiment at the LEP interaction point 1 is briefly reviewed [7, 8]. Finally, a possible implementation of this methodology for a fast luminosity monitor at FCC-ee is considered and its feasibility briefly discussed.

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Table 1: Expected BS rate (for $10 < \theta < 20$ mrad) and SB rate (for $E_\gamma > 0.5$ GeV) in the four beam energy configurations of FCC-ee

	Beam energy (GeV)	**BS rate (Hz)**	**SB rate (Hz)**
Z	45	$2\cdot10^6$	$6\cdot10^{11}$
WW	80	$5\cdot10^4$	$6\cdot10^{10}$
HZ	120	$8\cdot10^3$	$2\cdot10^{10}$
$t\bar{t}$	182.5	$6\cdot10^2$	$9\cdot10^9$

THE LEP-5 EXPERIMENT

At LEP with a luminosity $L \simeq 10^{31}$ cm^{-2} s^{-1} the expected SB photon rate is of the order of 3 MHz, which means about 100 Single Bremsstrahlung photons per bunch-crossing, 5-6 orders of magnitude greater than the Bhabha Scattering rate at small angles. Another important feature is the extremely collimated angular distribution of SB photons, the typical emission angle being $\theta_\gamma \simeq \frac{m_e}{E} \simeq 10$ µrad at LEP. In Fig. 1 a sketch of the LEP straight section 1 is shown: the photons travelling with the beams escape the beam-pipe at the beginning of the arc, reaching a detector placed at the end of the straight section, about 350 m far apart from the Interaction Point (IP).

The high SB photon rate implies to work in a multi-photon regime, in which the luminosity is obtained from a measurement of the integrated energy on the detector in a certain time interval, rather than from photon counting:

$$E_{meas} - E_{bckg} = AL \int_0^{E_{beam}} \epsilon(k) k \frac{d\sigma_{SB}}{dk} dk \qquad (1)$$

where k is the photon energy, L the integrated luminosity, E_{meas} the total measured energy in the time interval, E_{bckg} the background measured energy, E_{beam} the beam energy, A the acceptance, $\epsilon(k)$ the energy detection efficiency and threshold function, and $\frac{d\sigma_{SB}}{dk}$ the differential SB cross section. E_{meas} is the measured amount of energy deposited in the detector. E_{bckg} represents the background energy to be subtracted, and which is measured under the condition of no beam crossing in IP-1, with dominant contributions from the beam-gas bremsstrahlung and Compton scattered thermal photons. In Fig. 2 the expected spatial distribution of the deposited energy on the detector is shown, compared with the angular distribution of the SB. From a two dimensional fit of this distribution, the acceptance A is evaluated, obtaining in this way a measurement of the beam position in the transverse plane, and of the beam divergence at the IP.

The SB differential cross section $d\sigma_{SB}/dk$ in eq.(1) has to be evaluated taking into account the finite transverse sizes

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of the beams σ_x and σ_y, due to the large value of the impact parameter for the emission of SB photons at the LEP energy [4, 9–11]. The total SB cross section reduction with respect to the standard QED calculations due to the finite beam transverse sizes is $\sim 25\%$. Finally, in the case of LEP, the radiative corrections to the cross-section are less than 1%.

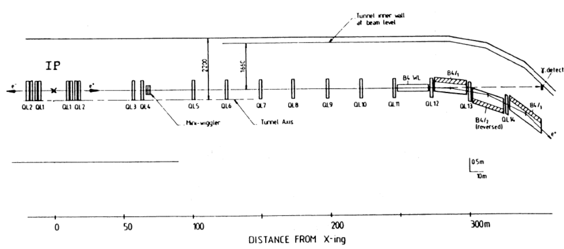

Figure 1: Sketch of the LEP straight section from the IP to the photon detector [7].

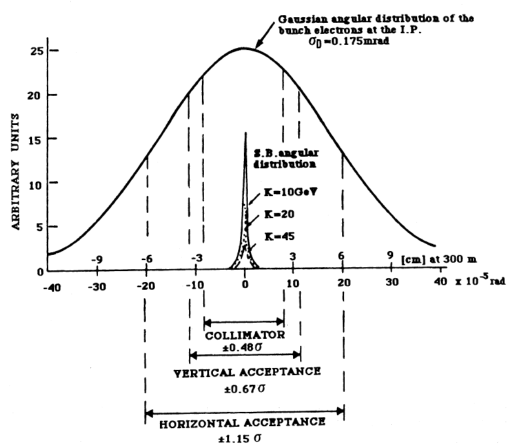

Figure 2: Angular distribution of the Single Bremsstrahlung photons due to the beam divergence [7].

Experimental Set-up

The LEP-5 experiment was approved by CERN in 1989 as a test experiment to be performed in IP-1[1], an interaction region without detectors since the four LEP experiments were installed in the even IPs. In normal conditions the beams were separated in order not to affect the beam lifetime. They were put into collisions in IP-1 only in the final 2 - 3 hours of a LEP fill, which used to last 10 - 12 hours. Moreover, also with colliding beams, the experimental conditions were different from even IPs. Since the beams were not optimized for collisions, the luminosity was lower by about one order of magnitude and the beam divergence smaller. The apparatus is sketched in Fig. 3: at the end of the straight section there was a thin aluminum window (2×5 cm^2) on the beam-pipe to allow photons to escape and to reach the photon detector placed about 350 m from the IP. The acceptance in IP-1 was only $A \sim 41\%$ due to the limited size of the window (it would have been larger in even IPs). The detector was an

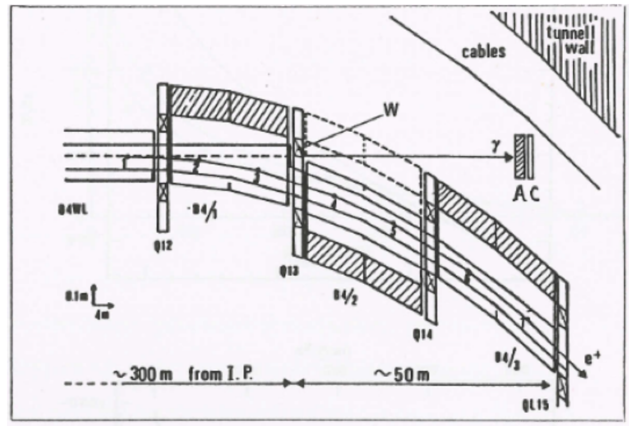

Figure 3: Sketch of the LEP-5 apparatus at the end of the straight section in IP-1.

electromagnetic calorimeter made of lead with embedded scintillating fibers as active medium [12]. In front of the calorimeter there was a 2 X_0 long absorber made of LiH, a low Z material to strongly suppress the synchrotron radiation (SR) background with respect to SB. The calorimeter consisted of a matrix of 7×6 modules each of $2.5 \times 2.5 \times 35$ cm^3 volume. The modules were built with a melting technique: molten lead was poured into a mould with spacers holding 144 steel tubes to accommodate the scintillating fibers of 1 mm diameter. The fibers were almost parallel to the flight direction of the incoming photons. From the read-out point of view each of the 6 central modules was divided into 4 separate channels to increase the spatial resolution in the central region of the calorimeter. Each readout channel was connected through a light guide to a photomultiplier.

Table 2 shows the overall reduction of the expected SR spectrum at LEP [13] with respect to SB photons, at the level of the detected energy in the calorimeter, as resulted from a detailed MC simulation including the LiH absorber and the calorimeter materials [7].

The calorimeter was installed in IP-1 during spring 1990, and data were taken during the following summer, in June - August 1990.

Lumininosity Measurement

In the following the best results, obtained during Fill 409 of LEP, are shown [7]. With separate beams in IP-1 the background from single beam radiation, due to the beam-gas bremsstrahlung and to the Compton scattered thermal photons, was measured. The beam-gas contribution was expected to be proportional to the beam current (of the positrons in this case), and to the density of residual gas in the beam-pipe, which is again proportional to the circulating currents. Also the Compton scattering of thermal photons was expected to be proportional to the beam current. Those two effects combined to produce the parabolic

[1] This is the site where now is installed the ATLAS detector at the LHC.

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Table 2: Expected photon energy spectrum – in GeV per bunch crossing (GeV/bx) – for SR exiting from the 2×5 cm^2 window on the beam-pipe at IP-1 of LEP [13] and upstream the LiH absorber, deposited energy in the active material of the calorimeter (scintillating fibers), and total attenuation factor, compared with the corresponding quantities evaluated for the global SB energy spectrum.

Photon energy	**Upstream LiH abs. (GeV/bx)**	**Deposited in in the fibers (GeV/bx)**	**Attenuation factor**
20 keV	$2.2 \cdot 10^6$	-	$< 10^{-9}$
100 keV	$1.8 \cdot 10^6$	-	$< 10^{-9}$
500 keV	$4.5 \cdot 10^5$	$2.1 \cdot 10^{-3}$	$4.7 \cdot 10^{-9}$
1 MeV	$4.8 \cdot 10^4$	$5.2 \cdot 10^{-3}$	$1.1 \cdot 10^{-7}$
2 MeV	$9.1 \cdot 10^2$	$7.2 \cdot 10^{-4}$	$7.9 \cdot 10^{-7}$
SB spect.	$1.7 \cdot 10^2$	2.2	$1.3 \cdot 10^{-2}$

behaviour shown in Fig. 4. When the beams were put into collisions a sudden signal increase was observed (Fig. 5), clearly showing the additional contribution of the SB photons. At the end of the collision regime, the last three points of Fig. 5, the integrated energy went back to the background level extrapolated as a function of the beam current. In

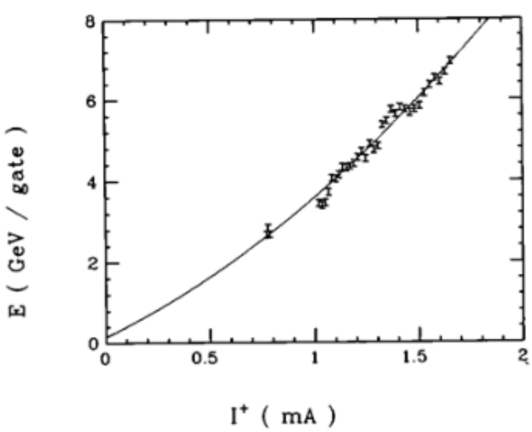

Figure 4: Deposited energy in the calorimeter with separate beams in IP-1 [7].

order to determine the absolute luminosity, the acceptance had to be evaluated from the spatial distribution of the energy on the calorimeter (Fig. 6). Finally, in Fig. 7 the result of the measurement is reported: each point corresponded to 10 minutes of data-taking, the statistical uncertainty was of the order of 1%. The *oscillating* behaviour of the luminosity in Fig. 7 was due to a β-waist scan during collisions. The systematic uncertainties were due to the background subtraction procedure (2%), the uncertainty in the evaluation of acceptance A (1.5%), the uncertainty in the SB cross section evaluation due to radiative corrections (< 1%), limited knowledge of the beam sizes (1%) and of the low energy effective threshold $E_{threshold}$ (efficiency) (1%). The total systematic uncertainty on the luminosity measurement

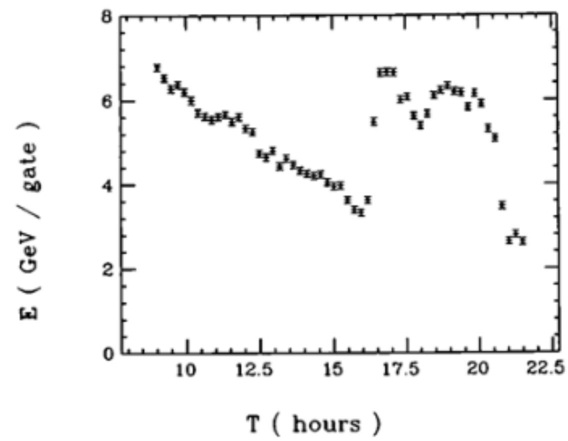

Figure 5: Signal of the Bremsstrahlung photons, collisions starts at about 16:00 hrs [7].

was ~ 3.2%. This could have been reduced to the $1-2\%$ level in different experimental conditions with higher luminosity and larger acceptance (e.g. at the LEP IP-even).

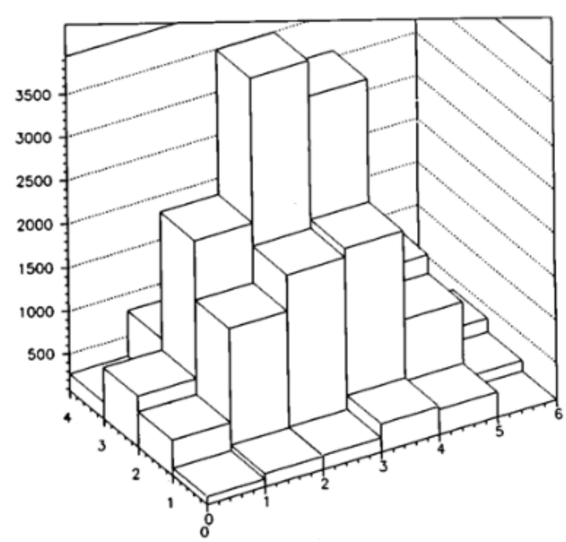

Figure 6: Spatial distribution of the deposited energy in the central modules of the calorimeter [7].

Compton Scattering of Thermal Photons

The LEP-5 experiment [14] (and independently another experiment at LEP [15]) measured for the first time the Compton scattering of the thermal photons present in the LEP beam-pipe against the high energy electrons. The LEP vacuum pipe could be considered as a black body at about 300 K temperature, hence filled with electromagnetic radiation with an energy distribution following the Planck law with a peak at $k_{max} \simeq 0.07$ eV. In the rest frame of the LEP electrons, a photon with energy k_{max} incident at an angle of 180° appears to have an energy $K^\star \simeq 2\gamma K_{max} \simeq 13.7$ keV due to the Lorentz boost. After a Compton back-scattering the photon gains another factor 2γ, then in the laboratory

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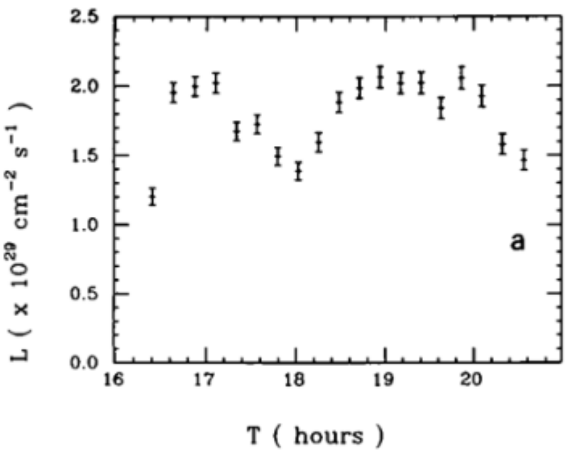

Figure 7: Luminosity as a function of time [7].

frame its energy will be $k \simeq 4\gamma^2 k_{max} \simeq 2.8$ GeV, well inside the energy range of the SB photons. Hence the Compton back-scattered photons constituted a relevant source of background for the measurement of the luminosity, of the same order of magnitude of the beam-gas bremsstrahlung, due to the extremely low vacuum pressure of LEP (of the order of 10^{-10} torr). The total background was measured with separate beams in IP-1, and in Fig. 8 the experimental spectrum of the integrated energy on the calorimeter is shown, compared with the Monte Carlo expectations for beam-gas bremsstrahlung and beam gas plus Compton backscattering [16]. The best agreement was found for an average number of beam-gas photons per bunch crossing of $\mu_{BG} = 0.44$ and of thermal photons $\mu_{TP} = 1.47$, and an effective detection energy threshold $E_{threshold} = 200$ MeV. It is worth noting that the threshold effect is clearly visible in the low energy end of the measured spectrum (Fig. 8), confirming the results of the MC simulation of the LiH absorber and the calorimeter response (Table 2). From these values an estimate of the temperature of the beam-pipe and the pressure of the residual gas in the pipe was obtained: $T \simeq 291$ K and $P \simeq 2.2 \times 10^{-10}$ torr, respectively.

Compton scattering of thermal photon could in principle decrease the beam lifetime; however the conclusion was that it could not degrade significantly the LEP performance [16].

Upgraded Set-up

During 1991 an upgrade of the experiment was performed in order to fully exploit the high rate capability of the luminosity measurement method [8]. In doing that, the possibility to measure the luminosity of the four bunches separately was also tested. This last feature would have been very important in case of polarization of LEP beams, since schemes with different polarization bunch per bunch were proposed [17]. A faster readout electronics was employed, able to process and store the signals from the calorimeter acquiring all the bunch crossings. Data were taken with this new readout on October-November 1991, but unfortunately beams were unstable when put in collisions in IP-1 due to a modified optics. However only few minutes of collisions were sufficient to prove the feasibility of the measurement (see Fig. 9), despite the beam optics was not optimized and the photons distribution was centered out of the window, causing a larger systematic uncertainty due to the evaluation of the geometrical acceptance from a tail of the distribution. Anyhow the collected data showed that the bunch per bunch luminosity could be measured with a statistical uncertainty of 0.2% in only 20 seconds.

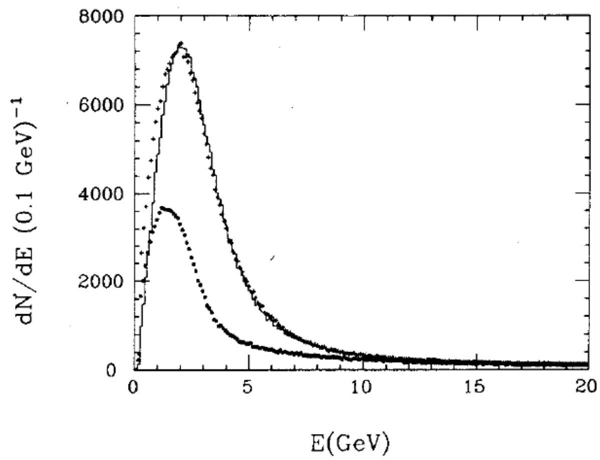

Figure 8: Spectrum of the deposited energy(histogram) compared with Monte Carlo simulation of beam gas (black points) and with beam gas plus Compton scattering (crosses) [14].

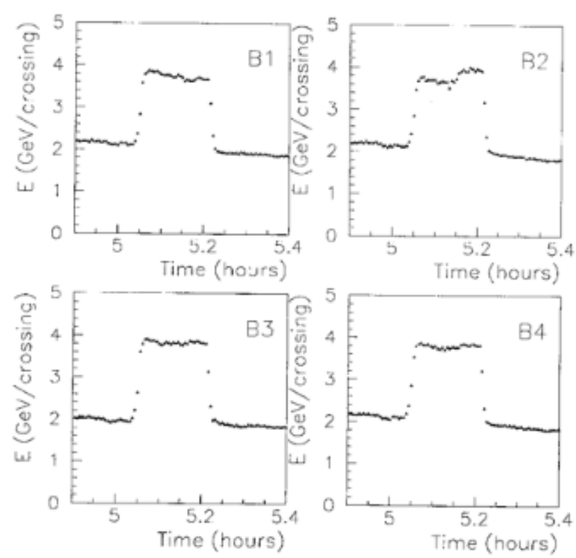

Figure 9: Deposited energy in the calorimeter for the four bunches separately [8].

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SOME CONSIDERATIONS ON THE FEASIBILITY AT FCC-ee

A luminosity monitor based on the detection of SB photons can reach very high rates at FCC-ee, as shown in Table 1, and could be very fast. The goal to reach $\sim 1\%$ precision on the absolute luminosity measurement for each single bunch would seem achievable, in principle, just adapting the methodology adopted at LEP and described above. It would require a good control of beam sizes and low energy effective threshold for the cross-section determination. Theoretical calculations could be improved implementing the radiative corrections. At FCC-ee the narrow angular collimation of SB photons is similar to LEP in all energy configurations, ranging from 10 to 3 μrad, with a beam divergence at IP approximately in the range $10 \div 100$ μrad. In case of a photon exit window at 50 m from IP, the beam spot can be only few mm wide, greatly improving the acceptance, and reducing the correlated systematic uncertainty. On the other hand the beam divergence and position at IP would be more difficult to be measured, requiring very good space resolution of the detector and to take into account the e.m. shower transverse sizes.

Preliminary results from detailed simulation studies to evaluate the various background sources at FCC-ee [18] show an overwhelming contribution concentrated in the forward direction, similarly to SB photons, from the beamstrahlung process [19, 20], in constrast with the LEP case, where it was fully negligible. Table 3 reports the expected total power and mean photon energy for the beamstrahlung [18] compared to SB.

Table 3: Expected total power and mean photon energy for the beamstrahlung process [18], compared to the SB process, and in the four beam energy configurations of FCC-ee.

	Beamstr. mean energy (MeV)	Beamstr. Total power (kW)	SB Total power (W)
Z	1.7	370	425
WW	7.2	236	60
HZ	22.9	147	40
$t\bar{t}$	62.3	77	2

In addition, the SR background will require a low-Z material absorber for the attenuation, whose length, shape, and material has to be carefully chosen (see e.g. Table 2) according to the simulation studies [18]. The impact of the corresponding worsening of the energy resolution and linearity of the downstream detector has to be carefully studied. The expected background contribution from the beam-gas bremsstrahlung and Compton scattering of thermal photons amounts to a fraction less than 10^{-4} of the SB signal [18], and can be neglected in all four energy configurations of FCC-ee.

In general the huge SB and background energy flux will require a very robust and radiation hard detector.

The main concern about the feasibility of a fast SB luminosity monitor at FCC-ee comes from the intense beamstrahlung background. On one hand, the signal-over-background power ratio is very unfavourable (0.1% at the Z pole) and the energy flux from beamstrahlung must be attenuated and rejected in some way. On the other hand, due to its very high power, it is anyhow necessary to have a beam dump for the beamstrahlung photons, in order for the machine to operate. The design of the overall layout of the beam dump would need to harmonize these two different requirements. The possibility of using special absorbers as in the case of SR must be judiciously studied. The huge rates of the high energy and penetrating SB photons might still allow the use of a calorimeter downstream a beam dump of several radiation lenghts, especially in the case of the softer beamstrahlung in the case of the Z pole energy configuration. The use of sweeping magnetic fields, or magnetized materials for additional background suppression, combined with possible discrimination based on the very different longitudinal e.m. shower profile of signal and background inside the calorimeter might be also exploited.

CONCLUSION

The luminosity measurement at LEP based on the SB process has been reviewed. A similar methodology could be implemented at FCC-ee. However in this case the huge background from beamstrahlung represents a major concern. Nonetheless a possible strong reduction of this background with respect to the SB signal might be achieved with the judicious exploitation of different attenuation and rejection techniques.

These solutions have to be carefully investigated and studied to understand the feasibility of a SB luminosity monitor at FCC-ee. Its main advantage would consist in a very fast and precise tool for machine operations, reaching the percent precision level on the absolute luminosity measurement, and separately for each bunch, therefore complementing the more precise but slower monitor based on BS.

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